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Original Article

Medial Prefrontal Cortex and Anterior Cingulate Cortex in the Generation of Alpha Activity Induced by Transcendental Meditation: A Magnetoencephalographic Study

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Previous EEG studies have shown that transcendental meditation (TM) increases frontal and central alpha activity. The present study was aimed at identifying the source of this alpha activity using magnetoencephalography (MEG) and electroencephalography (EEG) simultaneously on eight TM practitioners before, during, and after TM. The magnetic field potentials corresponding to TM-induced alpha activities on EEG recordings were extracted, and we attempted to localize the dipole sources using the multiple signal classification (MUSIC) algorithm, equivalent current dipole source analysis, and the multiple spatio-temporal dipole model. Since the dipoles were mapped to both the medial prefrontal cortex (mPFC) and anterior cingulate cortex (ACC), it is suggested that the mPFC and ACC play an important role in brain activity induced by TM.

Key words: transcendental meditation, magnetoencephalography (MEG), source analysis, medial prefrontal cortex, anterior cingulate cortex

Transcendental meditation (TM) is a mental stress reduction technique in which the practitioner closes his or her eyes and silently repeats a "mantra", a meaningless sequence of sounds specific to each individual, to promote a natural shift of awareness to a wakeful but deeply restful state [1]. EEG studies have shown that TM increases frontal and central alpha activity consistent with wakefulness [2].

Recently, a study using magnetoencephalography (MEG) has been reported analyzing the brain activity of a Yoga Master during meditation [3]. MEG has several theoretical advantages, including high spatial and temporal resolution, in identifying the localization of brain dipoles [4, 5]. Therefore, the use of MEG offers a new approach to the recording of TM-related brain activity.

In the present study, we used multichannel SQUID (superconducting quantum interference device) magnetometers to extract the magnetic field potentials that corresponded to TM-induced activities on EEG recordings, in an attempt to identify and localize the sources of the brain activities during practice of TM.

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Materials and Methods

Subjects. Sixteen healthy subjects (8 men and 8 women; mean age 38.8 years old, range 24–61 years old) participated in the study. We obtained their written informed consent prior to performing the experiments.

The study group consisted of 8 volunteers, aged 24 to 61 years old (4 men and 4 women; mean age 39.0 years old), who had been practicing TM regularly for an average period of 3.9 years. The control group comprised 8 persons aged 25 to 61 years old (4 men and 4 women; mean age 38.6 years old) who had not practiced TM or any other type of meditation before the study.

Tasks and data acquisition. The subjects of the study group were required to practice TM for 20 min. The control subjects were instructed to perform a sham task; a mock meditation involving a silent repetition of a simple non-mantra word (a simple number) with their eyes closed. We employed repetition of a single number as the sham task since it is equally non-challenging and simple as a TM task. The TM and the sham task were of equal length.

The recordings were made in a magnetically shielded room. The subject sat comfortably with his or her head under a whole-scalp neuromagnetometer that housed 148 SQUIDs (Magnes, Biomagnetic Technologies Inc., San Diego, CA, USA). Simultaneous EEG recordings were also performed with electrodes over the scalp, according to the International 10–20 method. Ag/AgCl electrodes were referenced to the linked ears. The recording time was divided into 3 parts: first, 5 min of rest before TM or the sham task with the eyes closed; second, TM or the sham task for 20 min; and third, 10 min of rest after the task, also with the eyes closed. The experimentalist verbally signaled the subjects to begin and end each task.

Both the MEGs and the EEGs were digitized at a sampling frequency of 678.17 Hz and filtered with a band-pass of 0.1 Hz – 200 Hz. Digitized data were stored and analyzed off-line, using further filtering through a 3–50 Hz band-pass filter. The duration of each epoch was 30 sec at regular intervals of 60 sec set by the internal trigger. Epochs were recorded 35 times, once a minute, over the whole session.

EEG. The data were sent to an NEC digital EEG recorder (SYNAFIT 5000). Topographical maps during these tasks were made by fast Fourier transformation (FFT) every 30 sec, which enabled us to confirm the change in distribution of α waves and the state of consciousness of the subjects. The EEG topographies consisted of 6 frequency bands: δ(2–4 Hz), θ(4–8), α_1(8–10), α_2(10–13), β_1(13–20), and β_2(20–30).

Analysis of EEG variables. The α power, index (content percentage), and mean frequency were obtained before and during TM practice using a software for EEG mapping, 'Atalas' (Kissei Comtec, Nagano, Japan). Data were conditioned with a Hanning window. These parameters in the 8–13 Hz window were averaged for a 60-s analysis period at frontal (Fp_1, Fp_2), parietal (P_3, P_4) and occipital sites (O_1, O_2), respectively, although mean frequency was obtained only at the occipital site.

The index of each band is obtained using the following formula:

$$Cp_\delta = \left(\frac{\sum_{i=6}^{21} \bar{S}n}{\sum_{i=6}^{21} \bar{S}n + \sum_{i=22}^{41} \bar{S}n + \sum_{i=42}^{66} \bar{S}n} \right) \times 100\ (\%)$$

$$Cp_\theta = \left(\frac{\sum_{i=22}^{41} \bar{S}n}{\sum_{i=6}^{21} \bar{S}n + \sum_{i=22}^{41} \bar{S}n + \sum_{i=42}^{66} \bar{S}n} \right) \times 100\ (\%)$$

$$Cp_\alpha = \left(\frac{\sum_{i=42}^{66} \bar{S}n}{\sum_{i=6}^{21} \bar{S}n + \sum_{i=22}^{41} \bar{S}n + \sum_{i=42}^{66} \bar{S}n} \right) \times 100\ (\%)$$

where $\bar{S}n$ is the averaged spectrum.

$$\bar{S}n = \frac{1}{12} \sum_{i=0}^{12} Sn$$

Repeated-measures ANOVA was performed to test condition-dependent differences in α power and index. Mean frequency and laterality of the parameters were analyzed with Student's *t*-test.

MEG. Based on visual inspection, α waves, which were active during TM or the control task and recorded simultaneously with the EEG, were detected after the offset was performed. As stated in the Results section, increased frontal and central alpha activities were observed during TM practice. We extracted 300–500 epochs of 100 ms duration (50 ms pre- and 50 ms post-α wave peak) of MEG waves in each subject.

Analysis of MEG data. We applied 3 different methods to analyze sources of the brain activities obtained during the task: the multiple signal classification (MUSIC) algorithm, equivalent current dipole (ECD) source analysis for both raw and averaged MEG data, and the multiple spatio-temporal dipole model method using the brain electric source analysis (BESA) Program [6]. MEG records were averaged for every cycle of α waves using individual negative peaks of α waves in the EEG as a trigger point. Source analysis using the MUSIC algorithm and BESA program were also performed from the averaged MEG data.

A GE Signa 1.5 T system was used for magnetic resonance imaging (MRI). 3D spoiled gradient pulse sequence (SPGR) images were used for overlays with MUSIC localization and ECD sources detected by MEG. The nasion was identified on MR images with the aid of high-contrast cod liver oil capsules.

Source analysis was performed with the MUSIC algorithm using Advanced Source Analysis (A.N.T. Software) on a PC/AT compatible personal computer. The principle of the MUSIC algorithm has been explained in detail in previous papers [7–13]. The advantage of using the MUSIC algorithm is that multiple asynchronous dipole sources can be drawn in contour maps that describe the appropriateness of a single dipole at each grid.

Raw data clustering was then performed using MEG data from 38 channels around the positions where electric current sources were predicted by the MUSIC algorithm. To identify the sources underlying the measured signals, the signal distributions were modeled with one equivalent current dipole (ECD). Only ECDs with both goodness-of-fit (GOF) and correlation exceeding 95% were accepted for further analysis. Estimated ECDs were superimposed on MRI pictures with common 3D coordinates and were correlated with the brain structure. A dipole fit using raw MEG data was drawn up by clustering of all these estimated ECDs for each subject. Dipoles were also obtained from averaged MEGs of the α waves using a single-dipole model.

Finally, to confirm the multiple sources obtained from MUSIC analysis and the ECD model, another analysis was performed with the multiple spatio-temporal dipole model using the BESA Program. This method allows spatio-temporal modeling of multiple simultaneous sources over defined intervals. Signal epochs for source analysis were defined on the basis of the global field power (GFP) [14]. We considered that when the residual variance (100-GOF(%)) was less than 5%, the adaptation of the dipoles would be significant.

Results

EEG and EEG topography. The EEG of TM practitioners appeared to show increased frontal and central α activity (diffuse high-amplitude α waves) during TM, which is in good agreement with the results of a previous report [2]. In contrast, control subjects showed ordinary occipital-dominant α waves during the sham task. EEG topography also indicated that TM practitioners showed substantially high α power over a large cortical area, but the control subjects showed little change during the sham task. Typical recordings of EEGs and EEG topographies during TM and the sham task are shown in Fig. 1.

Analysis of EEG variables. Table 1 presents means and standard errors for the α power and mean frequency of α waves before and during the task. Means of bilateral EEG parameters at each site were used for the analysis since no significant laterality was found in any parameters obtained. Repeated-measures ANOVA revealed a significant effect ($p = 0.034$), with higher α power values in the frontal area during TM practice. There was a tendency for the α power in the parietal area to be increased by TM practice ($p = 0.071$). No significant effect was seen either in the α power in the occipital area or in the α index (data not shown) in any areas. The mean frequency of α waves in the occipital area significantly decreased during TM ($p = 0.0004$). No significant change was seen in mean frequency during the sham task.

Source locations using MUSIC. Using superimposition of contour maps from the MUSIC algorithm onto MR images (Fig. 2), the diffuse high-amplitude α waves of TM practitioners were predicted to originate from the medial frontal cortex and

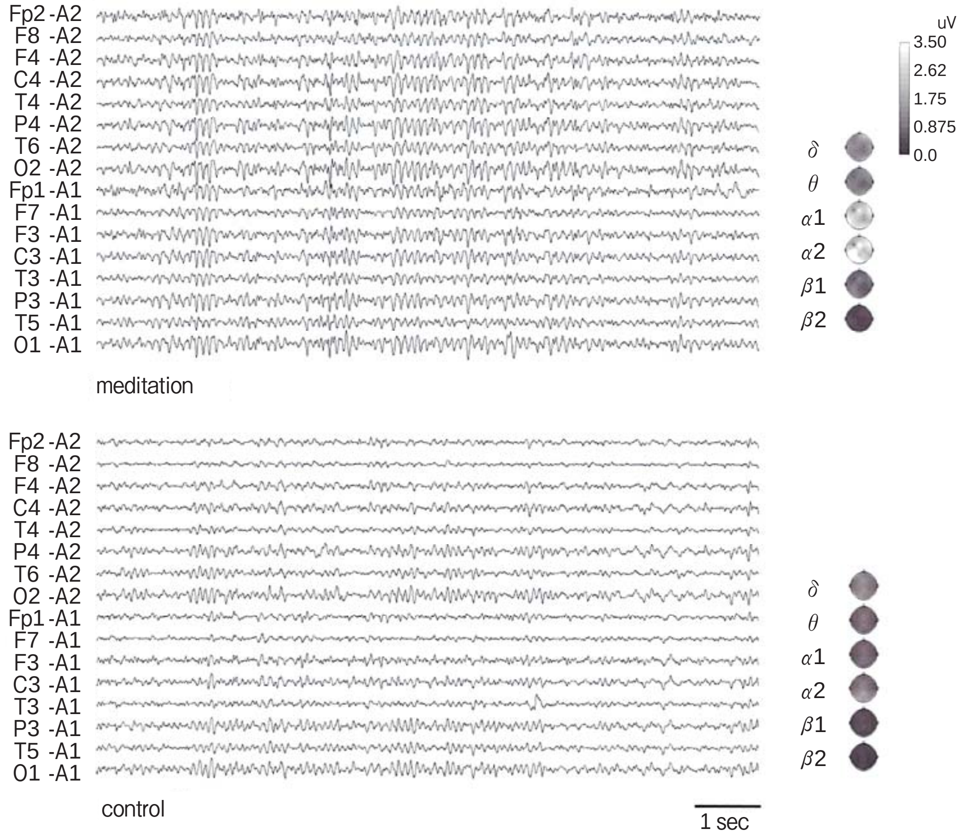


Fig. 1 Comparison of raw EEGs and EEG topographies. The EEG of a TM practitioner shows diffuse high amplitude α waves. There was a marked increase in α power during TM (top row). The control subject shows occipital-dominant α waves, and little change was seen in α power during the sham task (bottom row).

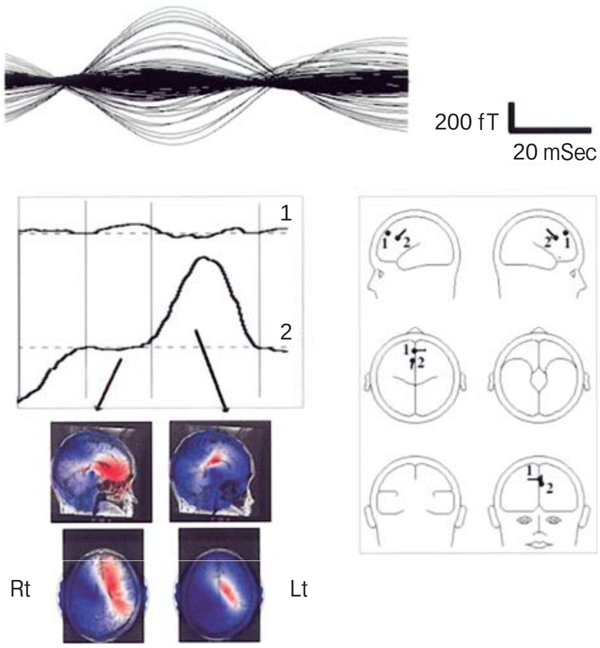
Table 1 Means and standard errors of the alpha power and mean frequency before and during task

Variable	before task	during task	*P* value
Alpha power (μV)			
frontal			
TM	27.2 ± 4.5	33.8 ± 4.8	
sham task	23.9 ± 4.0	22.3 ± 3.0	0.034
parietal			
TM	33.1 ± 5.4	37.4 ± 6.3	
sham task	28.6 ± 4.3	27.4 ± 3.3	0.071
occipital			
TM	39.8 ± 6.1	40.9 ± 7.3	
sham task	30.9 ± 4.6	29.3 ± 2.7	0.567
mean frequency (Hz)			
TM	11.33 ± 1.44	9.66 ± 1.23	0.00004
sham task	11.23 ± 0.65	11.36 ± 1.39	0.751

Note. Entries are means ± standard errors. Mean frequency was obtained from the occipital area.

Fig. 2 Top, 148 channel superimposed MEG waveforms for 1 subject; Upper left, The waveforms 1 and 2 showed the temporal changes in global field power (GFP) of the dipole sources 1 and 2 (head diagrams of BESA), respectively; Lower left, MUSIC localizations onto MR images. The 2 left images were obtained from the analysis of the first segment of GFP waveforms (left arrow), and the 2 right images were obtained from the second segment (right arrow). These images showed 2 sources at the medial frontal cortex (left) and a large area including the cingulate cortex (right). Right, Multiple dipole analysis using BESA indicated almost the same current dipoles as the source locations using MUSIC. The line and its length from each point indicate the direction and magnitude of the dipole current, respectively.

Fig. 4 Dipoles obtained from averaged MEGs of diffuse α waves. These were located in the central area between the mPFC and ACC.



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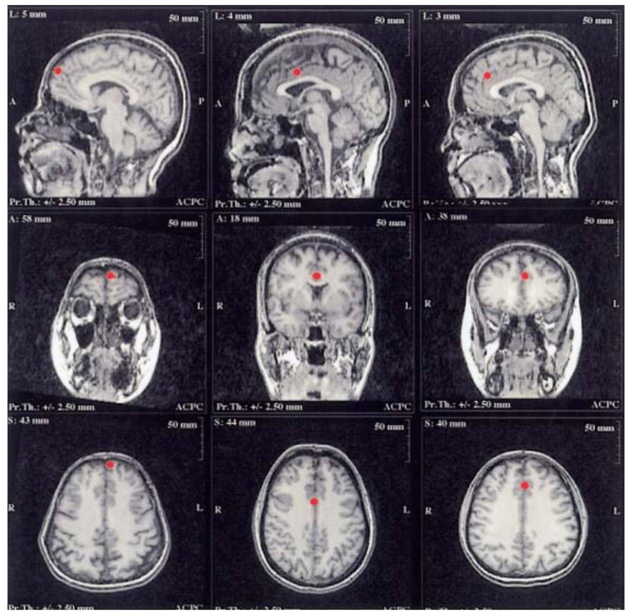

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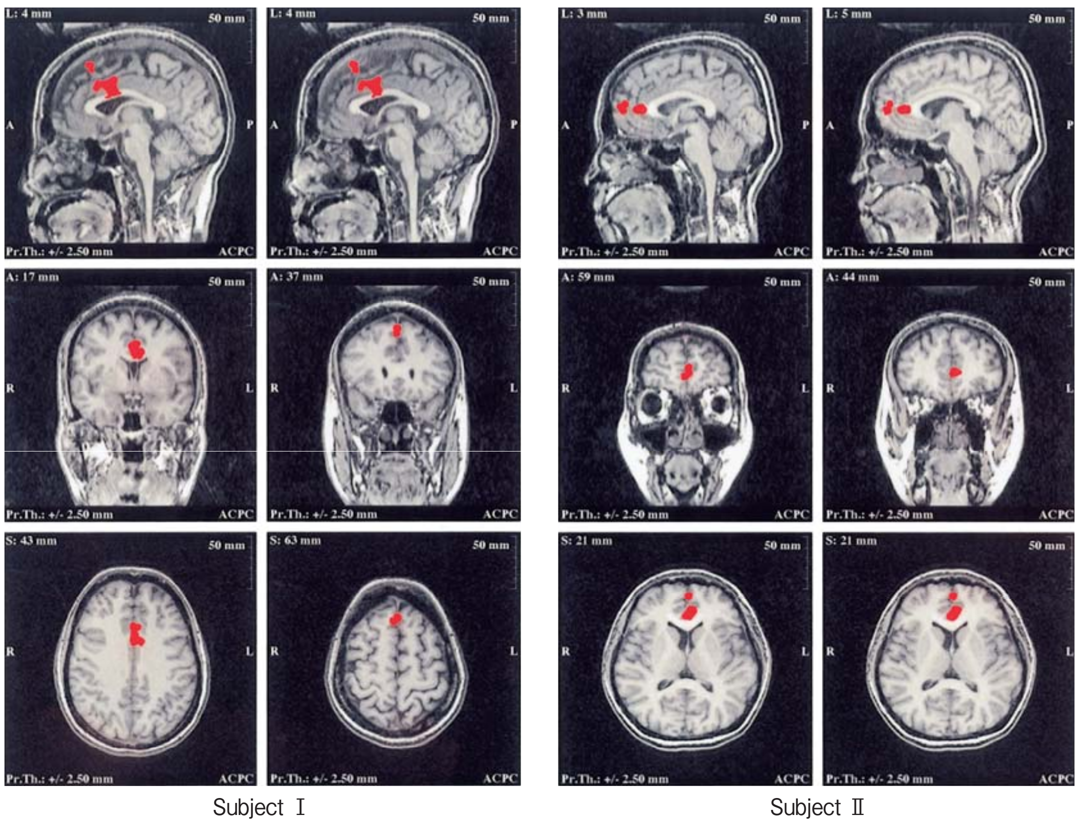

Fig. 3 Raw data clustering using a single-dipole model. These 2 subjects showed clusters at both the medial prefrontal cortex (mPFC) and anterior cingulate cortex (ACC).

Table 2 Results of dipole fitting using raw MEG data during TM

Subject	Age (years)	Sex	Dipole Fit	
			mPFC	ACC
1	24	M	+	+
2	35	M	+	+
3	35	M	+	+
4	61	M	−	+
5	32	F	+	+
6	36	F	+	+
7	37	F	+	+
8	49	F	+	−

mPFC, medial prefrontal cortex; ACC, anterior cingulated cortex.

a large area including the cingulate cortex. On the contrary, the MUSIC algorithm predicted that the occipital-dominant α waves during the sham task mainly originated around the calcarine sulcus in the occipital lobe. Because the results of the sham task were completely different from those for TM, we proceeded to perform further source analysis of brain activities during TM.

The single-dipole model and the averaging method. Results of dipole modeling using the extracted components are shown in Fig. 3 and Fig. 4. A typical recording with raw data clustering using a single-dipole model showed clusters at both the medial prefrontal cortex (mPFC) and anterior cingulate cortex (ACC) (Fig. 3). Table 2 shows the locations of the dipoles of all subjects using raw MEG data. Of the 8 subjects, 6 showed 2 distinct clusters, while the other 2 subjects showed only 1 cluster in either of the 2 areas. Both the mPFC and ACC sources were continuously observed over the whole TM session. Dipoles obtained from averaged MEGs of diffuse α waves were in the central area between the mPFC and ACC (Fig. 4).

Source locations using BESA. Two current sources that corresponded to those estimated by MUSIC analysis were also identified with the BESA program (Fig. 2). Locations and directions of the sources within the spherical head model are shown in Fig. 2.

Discussion

Previous EEG studies on TM have reported increased frontal and central α activity or α power [2, 15], but magnetoencephalographic studies during TM have not been reported to date. In the present study, we found from EEG analysis that TM practice increased α power in the frontal area. Provided with the results in EEG, we performed source analyses of α activities during TM. We used 3 different MEG analysis programs, each of which has its own characteristics.

Asada *et al.* [16] performed source analysis for frontal midline theta rhythm (Fmθ) using the MEG system. In their study, consecutive theta rhythms often appeared on simultaneous EEG recordings, and they extracted MEG components that were related only to the Fmθ rhythm using EEG peak potential as the trigger. Averaged theta components of MEG signals were analyzed with a multi-dipole model. They showed that the use of averaging for the background rhythmic activity eliminated the effects of variability of the other activities unrelated to Fmθ, facilitating the identification of Fmθ-dependent activity generated by Fmθ sources. In the present study, along with raw data clustering, averaged MEG recordings of diffuse α waves were obtained from all the extracted components using their method.

Ninomiya *et al.* [17] have suggested that the MUSIC algorithm is an effective tool for analyzing higher functions in the central nervous system. The advantage of using the MUSIC algorithm is that, regardless of the number of dipole sources, it can estimate the source locations with a 3D search [13]. In the present study, the MUSIC algorithm gave 2 different dipole sources, the medial frontal and cingulate cortices. The single ECD model has been used widely for current source analysis [13]. Although the model has high spatial resolution, it is valid only for discrete sources of a small spatial extent [18]. Thus, the ECD model is not very suitable for analyzing complex processes such as higher brain functions because of its limited ability to measure multiple electrical current sources. In order to compensate for this defect, we performed raw data clustering using MEG data from 38 channels around the positions where electric current sources were estimated by the MUSIC algorithm. The results of the single ECD model and averaging method indicated almost the same current sources as those predicted by the MUSIC algorithm. Another multiple dipole analysis using BESA indicated the same locations as the single ECD model. The similarity of the predicted regions for the dipole sources from the 3 different analysis methods provides convincing evidence that the dipoles for the diffuse high-amplitude α waves are localized to both the mPFC and ACC.

The search for the functional nature of the ACC has shown that the ACC has outflow to the autonomic, visceromotor and endocrine systems [19]. Travis and Wallace [20] demonstrated that TM can be distinguished from a simple resting state with the eyes closed by several physiological factors, such as lower breathing rates, lower skin conductance levels, and higher respiratory sinus arrhythmia levels. Biochemical experiments have indicated that baseline levels and acute responses to laboratory stress showed significantly different changes or trends toward significance for four hormones — cortisol, growth hormone, thyroid-stimulating hormone and testosterone — in plasma or serum samples in 2 groups practicing either the TM technique or a stress education control approach [21]. These findings of autonomic patterns or hormonal changes during TM are in accord with investigations related to the ACC.

Furthermore, Devinsky *et al.* [22] showed that rostral Brodmann area 32 (mPFC) is connected to parts of the autonomic brainstem nuclei. The prefrontal cortex and the limbic association cortex, including the ACC, are known to be mutually connected and to form a neural network [23]. The ACC and mPFC are also considered to modulate internal emotional responses, probably by controlling the neural activity of components of the limbic system, such as the amygdala [24–26]. Although there has to date been no clear evidence that either the ACC or mPFC is the center of comfortable or relaxed sensations, our data suggest that these brain areas might contribute to the unique comfortable sensation during TM by forming a diffuse alpha rhythm. Further studies will be required to elucidate whether these areas do have a pivotal role in the effects of relaxation techniques.

Our results, together with those from previous findings, suggest that the mPFC and ACC have an important role in the mechanism underlying the unique mental state produced by the practice of TM.

In conclusion, we have demonstrated that MEG is useful for studying the changes in brain activity that occur during the practice of TM. Using 3 different MEG analysis programs, the sources of diffuse high-amplitude α waves during TM were mapped to regions of both the mPFC and ACC.

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